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by

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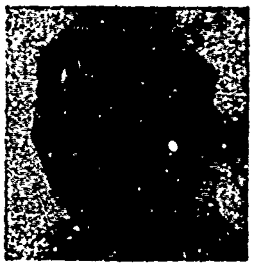

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Introduction

The Canadian Forces have made intensive use of non-destructive testing during the past twenty years, both in the well publicized area of quality control, and also in maintenance.[1] It may encourage Canadians to know that our Forces have not lagged behind in the utilization of this modern technology but have, in fact, been pioneers in some of their applications of non-destructive testing.

One example might be given in order to set the stage for this paper and give some engineering significance to the topic. Historically, the navies of the world have established the corroded state of ships' boilers by removing selected tubes, sectioning them and gauging the wastage with a micrometer ("wear and waste" testing). The expected service life of the boiler was then predicted from this very expensive data. This is no longer a routine procedure with the Canadian Forces—because it has been shown that the same data (indeed, more data) can be obtained about the boiler at much less cost using non-destructive testing.[2] The concept of evaluating corrosion in naval boilers with NDT was introduced and pioneered in Canada and has been of considerable interest to other countries. This is "Non-destructive Testing for Corrosion Evaluation."

Before considering a number of examples of NDT applications in corrosion evaluation, an introduction will first be given to the tools—the NDT procedures. The value of using these techniques for examining a number of types of corrosion attack will then be outlined.

Figure 1
Radiograph of soot-blower gooseneck showing wall thinned by internal wastage

The NDT Techniques

1. *Radiography*

Radiography works on the shadow picture principle. The radiation used—X-rays, as produced by electric apparatus, or gamma rays, as emitted by radioisotopes—is partially absorbed by the object being inspected, and the shadow image is recorded on a photographic film. Accordingly, differences in metal thickness result in darkness (density) differences on the film. In corrosion studies, these density differences indicate relative amounts of metal loss.

In corrosion evaluation, radiography has the very important feature of giving the corrosion engineer a general impression of the nature, the distribution and the extent of the areas of wastage. It may be possible then, from the radiographs, to assess both the corrosion mechanism and also the amount of damage.[3] The radiograph is a permanent record; the engineer can, therefore, assess the results of the NDT himself and not rely completely on the interpretation of his technician. The testing technique has no inherent calibration requirements and one does not really have to look for possible sources of error in evaluating results. Radiography has the additional value of giving information about the configuration of hidden components (sleeves, spindles, springs) as well as showing non-metallics which may be associated with the corrosion problem (shellfish growth, deposits, paint).

The major limitation of radiography is that access to both sides of the component in question is required. Also, the costs of inspection may be high relative to other NDT techniques. In addition, X-rays and Gamma rays are inherently dangerous and must therefore be used at inconvenient hours to avoid working personnel.

2. *Ultrasonics*

The ultrasonic method normally utilized in non-destructive testing evaluations of corrosion damage is the pulse-echo technique.[4] Here, the distance between the surface (to which the ultrasonic transducer is applied) and a subsurface interface is determined by the time (in microseconds) taken for the pulse to be reflected. The technique is very sensitive and accordingly very small interfaces can be detected by this method.

In corrosion evaluation, ultrasonics has the important advantage that access to only one side of the component is required. Also, the cost of the testing procedure is relatively low, although capable, experienced ultrasonics technicians are required if reliable results are to be expected.

The major disadvantage of ultrasonic testing for corrosion damage is that the evidence is normally assessed in the field by the ultrasonics technician, and the engineer must therefore rely heavily on the technician's judgment, or must accompany him on the job in order to gain experience in applying and interpreting ultrasonic signal displays.

3. *Eddy Current Testing*

In eddy current testing, the probe (a coil with alternating current normally in the KHz range) is

applied to the component and the effect of the presence of the component in its resistance to the field created by the coil is indicated. The eddy current effects are sensitive to compositional and metallurgical changes as well as to thickness and discontinuities, and the results may, therefore, be difficult to evaluate unless a number of the variables are standardized.

In corrosion studies, eddy current tests are devised in order to evaluate specific problems: corrosion in condenser tubes of known composition,[5] corrosion under aircraft skin of a known composition and heat treatment,[6] cracks in the surface of a neoprene-coated maraging steel component. Once the instrument has been suitably standardized, this inexpensive testing can in some instances be performed by relatively inexperienced personnel; however, more frequently, the interpretation of the results is open to considerable question.

4. Magnetic Particle Inspection

When a ferromagnetic (steel or iron) component is magnetized—by another magnet or by a coil carrying electrical current—and fine iron particles are spread onto the component's surface, the particles will cling to and outline any discontinuity, since the discontinuity breaks the magnetic field.

Surface corrosion cracks can readily, and at very little expense, be outlined in this way.[7] Unless the cracks are very small, they can be detected even in the presence of corrosion products or paint.

5. Dye Penetrant Inspection

When a dye with low surface tension is applied to a component, it will penetrate into surface cracks and discontinuities. If the surface dye is then washed off and the part is subsequently treated to draw the dye out of the discontinuities, the configurations of the discontinuities will be outlined.

Surface corrosion cracks can readily, and at little expense, be evaluated by using dye penetrant techniques;[8] however, corrosion products tend to absorb the dye, masking the cracked areas, and it is therefore necessary to clean surfaces thoroughly for dye penetrant inspections.

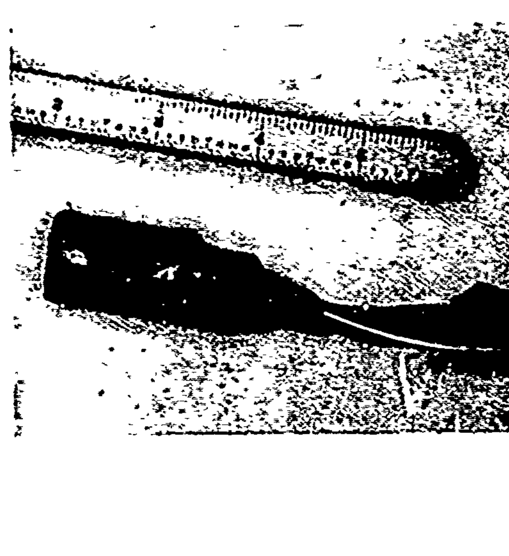


Figure 2
20 MHz ultrasonic immersion probe which is inserted into superheater tubes (Figure 3) for wastage evaluation

6. Other Techniques

A number of other non-destructive testing techniques are used in corrosion evaluation: vibration analysis, spectrometric oil analysis, infra-red testing[9] and various visual methods. This paper will, however, be limited to a discussion of those procedures traditionally classified as non-destructive testing.

Corrosion Evaluation

When considering corrosion damage, the corrosion engineer wants to establish the answer to two basic questions:

1) What is the nature of attack?

and

2) What is the extent of the corrosion damage?

If non-destructive testing helps to establish the answer to the first question its usefulness is significantly enhanced. Normally NDT is utilized to answer only the second question, on the assumption that the corrosion specialist has already ascertained the corrosion mechanism.

In this paper, the corrosion problems discussed will be classified in terms of the nature of the corrosion damage, starting with the most general wastage and ending with very localized cracking degradation.

1. General Wastage

Some wastage mechanisms such as corrosion-erosion and high temperature oxidation result in a general loss of metal. Visual examinations of components suffering from external attack by such mechanisms may readily indicate the nature of the attack, but the extent of the damage may not be apparent. In other instances, where the attack is internal, the wastage may be detected only by utilizing non-destructive tests.

The failure of a sootblower gooseneck on a destroyer escort was shown, by radiography, to be due to general wastage, Figure 1. The thick-walled casting had wasted internally by corrosion-erosion, an attack which was not apparent on the outside of the gooseneck until failure took place. In this instance, radiography had the important virtue of illustrating the whole problem clearly. Once this wastage problem was understood and the areas of severe attack known, the goosenecks on other ships could be readily evaluated with ultrasonics. Where wastage is general and uniform, ultrasonics can normally be applied to greatest advantage as a thickness measuring instrument.

The evaluation of this general corrosion problem by radiography resulted because the sootblower could be X-rayed at right angles to the wastage and the casting wall thickness was therefore outlined. In many instances, access is not such that a radiographic examination of this type can be made. For example, the central problem encountered in DDE boiler tube wastage is that of the general external oxidation of one side of the superheater tubes.[2] Here, the thinned area cannot be X-rayed at right angles to the wastage "in situ"; indeed, there is virtually no access to the outside

of the superheater tubes. X-rays can be taken of small areas of the wasted superheater tubes with a radiographic film placed inside the tube, but accurate thickness measurements cannot be made using this radiographic technique.

Ultrasonics provides a much better answer. The ultrasonic probe, illustrated in Figure 2, can be inserted into the tube, the tube flooded and thicknesses readily established as shown in Figure 3.[10] The immersion probe utilizes a 20 MHz transducer (high frequency because the tube is so thin—0.14" to 0.04").

A third example of general wastage is that of the exterior of a 12-inch pipeline at the Colwood Oil Depot.[11] It was obvious, from a superficial examination, that the large pipeline had wasted externally—but the extent of the wastage was not apparent. This was an ideal situation for ultrasonic pulse-echo testing and tests were performed at many locations along the pipeline—in this instance confirming that the line had wasted very little and did not need replacing.

2. *Pitting Corrosion*

While the ultrasonic testing of the pipeline revealed the extent of the external wastage, there was some concern that internal pitting may also have taken place. A radiographic examination was more useful in this case—to establish both the general distribution and the depth of the pits. In fact, the 12-inch pipeline did not contain significant internal attack.

An example of a small stainless steel tube containing pits is shown in Figure 4. Here, the pits in the leaky 0.5 inch diameter tube could not be detected visually on the surface of the tube but were revealed by radiography. These pits were also readily detected in the stainless steel tubing using

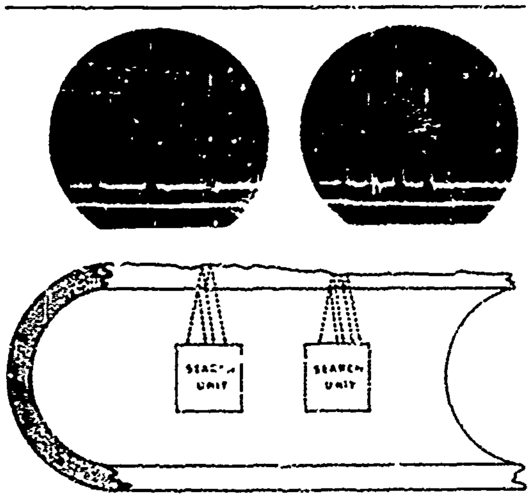
Figure 3
Ultrasonic signals from superheater tube wasted (0.06") right and original (0.125") left

Figure 4
0.5" Diameter stainless steel tube showing small pit (which was not detected visually on the exterior of the tube)

Figure 5
Schematic drawing showing a "Probolog" eddy current evaluation of a pitted condenser tube

Figure 6
Aircraft forging showing exfoliation corrosion on one surface

Figure 7
Dezincification attack of tube sheet of DDE turbo alternator air ejector



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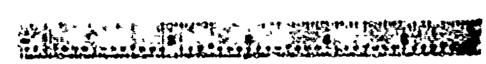

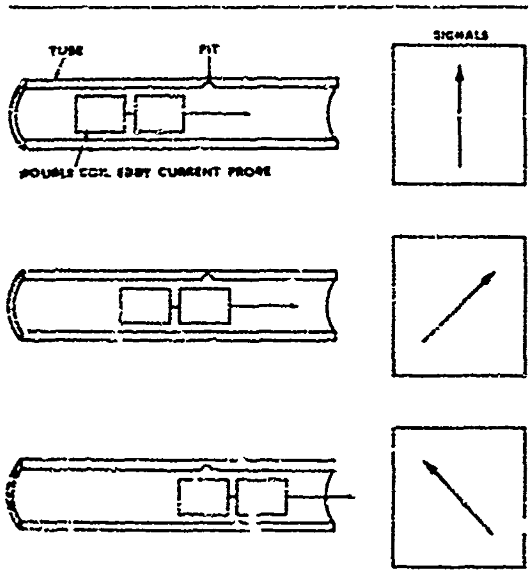

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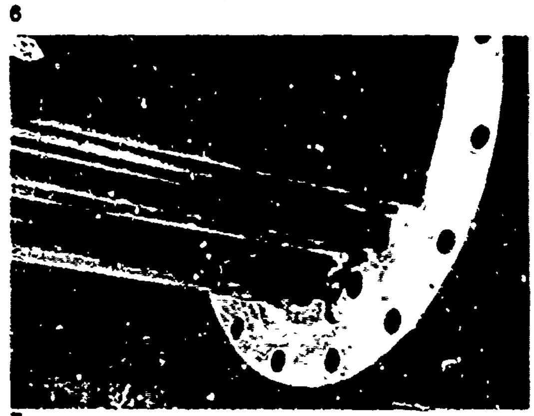

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an eddy current coil. The use of eddy current techniques for the detection of pitting in tubing is not new to the Canadian Forces. In the early 1950's, when brass condenser tubes were used in Canadian Forces ships, corrosion in these tubes was common and a device called a Probolog was used to detect the corrosion action, as illustrated in Figure 5. The device was very sensitive, however, and it was difficult to differentiate between serious pitting and superficial pitting. Recently, problems with condenser tubes have again been reported (it is understood that the USN is working on an ultrasonic probe and the fact that the RN has discussed the use of a new eddy current unit for the purpose of detecting condenser tube corrosion may suggest that they too have had corrosion problems in their copper-nickel tubes), and eddy current units may therefore be required for the evaluation of the copper-nickel tubes presently used in the condensers of Canadian Forces ships.

3. *Intergranular Corrosion*

The extent of intergranular attack cannot be satisfactorily evaluated by radiography (where the extent of damage is determined by the amount of metal missing). Intergranular attack can, however, often be detected by radiography—and the detection of the very presence of intergranular attack is helpful.

Corrosion action was noted on the surface of an aircraft forging as shown in Figure 6. Here, the question was that of determining the seriousness of the damage non-destructively. An ultrasonic evaluation from the uncorroded side readily revealed the extent of the intergranular corrosion attack—that it was relatively shallow and that the strength of the component had not been significantly reduced.

In aircraft, corrosion of this kind is frequently found in crevices and riveted laps. It has been shown that hidden corrosion can be evaluated in aircraft skin from the corrosion-free surface by means of eddy current devices. A phase sensitive eddy current unit can measure the thickness of sound metal from the uncorroded side,[6] thus establishing the extent of the corrosion damage.

4. *Dezincification and Dealuminification*

The extent to which dezincification has weakened brass components is always of concern to the corrosion engineer. While radiography can show the presence of the dezincification attack, this technique is relatively insensitive and, in any event, most dezincification problems cannot be so evaluated because of access difficulties.

One example of a dezincification problem which is being evaluated with non-destructive testing is that of the tube sheets of the turbo alternator air ejectors on the destroyer escorts. Here, as shown in Figure 7, the dezincification problem is found inside the unit (the heat exchanger tubes being cooled by sea water on the outside). Accordingly, the extent of the dezincification attack can be detected with ultrasonics from the clean accessible side of the tube sheets. (Most heat exchangers pump the sea water through the tubes and the dezincification attack is present on the accessible side). Ultrasonic signals of the type shown in Figure 8 were obtained from corroded and non-corroded areas. In this instance, a double transducer probe was used such that the initial pulse is not shown; however, it can be noted that the bold horizontal white line in the figure extends 7½ white markings for the 0.75-inch plate (on the left) and only 5 white markings for the dezincified metal.

The extent of dezincification attack can readily be evaluated with ultrasonics because the attack is general. Problems with dealuminification are somewhat different, since the attack is much less uniform. However, ultrasonics also appears to be the most useful method for evaluating the extent of the branching dealuminification attack.

5. *Corrosion-Fatigue*

While fatigue cracks tend to be difficult to evaluate with radiography, because the crack is tight and represents very little metal wastage, corrosion-

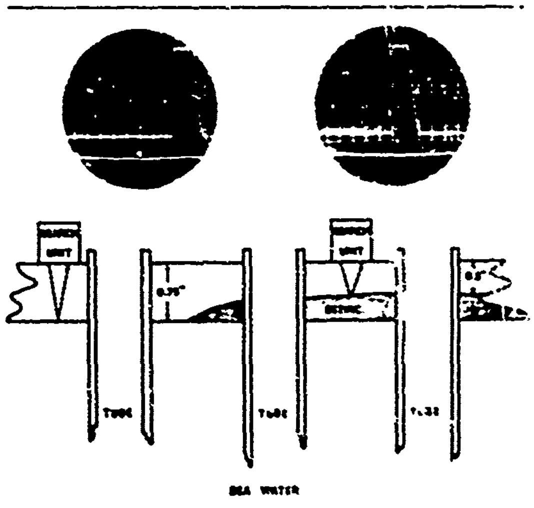

Figure 8
Ultrasonic signals (5 MHz double transducer) from uncorroded (left) and dezincified (right) areas of tube sheet. (Note Figure 7)

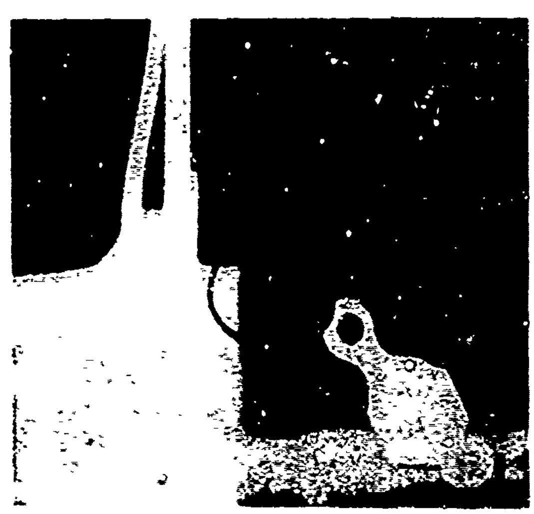

Figure 9 (far right)
Radiograph showing corrosion fatigue crack in the leading edge of a flap extrusion in a jet aircraft

fatigue cracks are more readily evaluated by this NDT technique because corrosion action tends to widen the crack, at least at the metal surface.

Many examples of the detection of corrosion-fatigue cracking with NDT can be given. One of the early boiler tube radiographic examinations conducted by our laboratory showed that circumferential cracks were present in frigate boiler tubes.[3] In this instance, the radiography not only revealed the circumferential cracks (and the tubes were accordingly plugged to ensure that failure would not take place in service) but also showed the internal deposits which produced the cracks (by overheating, upsetting and producing high residual tensile stresses[12]). Similar cracks are present in destroyer escort economizer tubes near the header end, but these tubes can be evaluated by means of borescope visual techniques because of the close proximity of the cracking to the tube end.

A more recent example of the evaluation of corrosion-fatigue cracking with NDT was the radiographic detection by our laboratory of cracks in the flap extrusions of jet aircraft, Figure 9. Only well-developed cracks could be detected by the X-ray technique, but the very fine cracks could be established by means of a fluorescent dye penetrant method. Eddy current methods might also have been used to advantage for "in situ" examinations had the leading edge of the extrusion not been partially covered by aircraft skin.

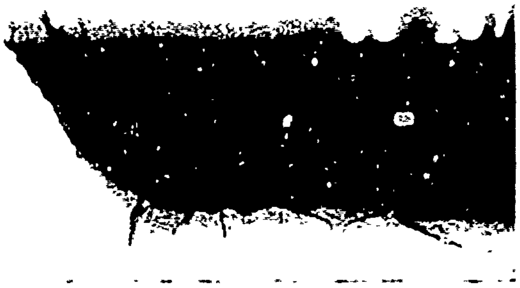

Figure 10
Radiograph showing stress corrosion cracks in stainless steel heat exchanger housing

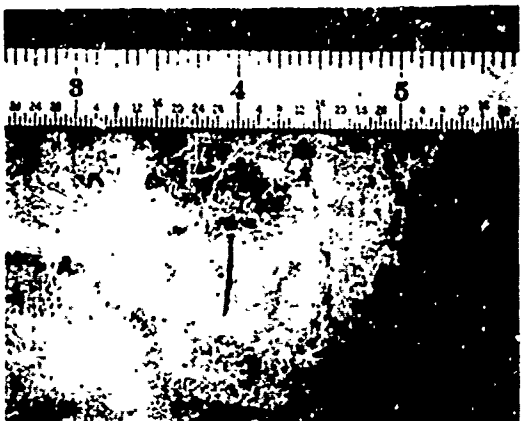

Figure 11
Maraging steel structural component showing hydrogen embrittlement crack outlined by a magnetic particle indication

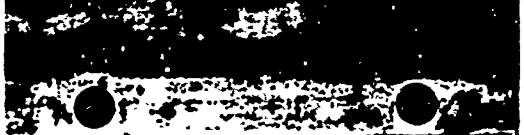

Figure 12
Eddy current scan across hydrogen crack in maraging steel (from A to B in Figure 11) through 0.02" of neoprene

6. Stress Corrosion Cracking

Stress-corrosion cracks, by their nature, are normally very fine and represent very little metal wastage. Accordingly, the early stages of cracking may be difficult to detect with radiography; however, once the cracks are more extensive and are opened up by the associated tensile stresses, they can normally be detected very easily.

A stainless steel body of a heat exchanger was evaluated at DREP recently when it was noted that the external insulation was wet. X-ray examination showed a classical stress corrosion cracking picture, Figure 10. It might be added that a complete X-ray of the heat exchanger showed that the corrosive attack was extensive, and the heat exchanger needed replacing rather than repairing.

Stress corrosion cracks can be and are being detected by the other NDT methods. Cracks can readily be evaluated with ultrasonics,[14] with eddy current techniques and by magnetic particle and fluorescent dye penetrant techniques.

7. Hydrogen Embrittlement

In principle, the very fine hydrogen embrittlement cracking should be most difficult to evaluate with radiography because the branching cracks are not normally as extensive as those associated with stress-corrosion cracking. A recent example of hydrogen embrittlement is that of the cracking of cathodically protected maraging steel. The short, relatively unbranched cracks—due primarily to the high residual stresses present in the heat affected zone of the weld – could, however, readily be detected by radiography. Experimentation showed that the small crack illustrated in Figure 11 by a magnetic particle indication was detectable at considerable deviation from right angles to the foil (namely, from 80° to 120°).

These cracks, which originated on the inside surface of the foil, were easy to detect with ultrasonics once the neoprene was removed, whether they extended through to the surface or not, and some cracks were also detected through the neoprene which covered the foil. The ultrasonic technique was, however, relatively slow. Eddy

Table 1
Non-destructive testing techniques in the evaluation of various corrosion problems

CORROSION TYPE	RAD	U/T	E/C	MPI	DPI
HIDDEN WASTAGE OF UNKNOWN MECHANISMS	BEST GENERAL TECHNIQUE	LIMITED	LIMITED	N.A.	N.A.
GENERAL WASTAGE	POOR	BEST GENERAL TECHNIQUE	LIMITED	N.A.	N.A.
PITTING CORROSION	BEST GENERAL TECHNIQUE	CAN DETECT	GOOD METHOD	N.A.	N.A.
INTERGRANULAR CORROSION	CAN DETECT	BEST GENERAL TECHNIQUE	GOOD METHOD	CAN DETECT	CAN DETECT
DEZINCIFICATION	CAN DETECT	BEST GENERAL TECHNIQUE	N.A.	N.A.	N.A.
CORROSION FATIGUE	BEST GENERAL TECHNIQUE	GOOD METHOD	GOOD METHOD	GOOD METHOD	CAN DETECT
STRESS CORROSION CRACKING	GOOD METHOD	BEST GENERAL TECHNIQUE	GOOD METHOD	GOOD METHOD	GOOD METHOD
HYDROGEN EMBRITTLEMENT CRACKING	CAN DETECT	BEST GENERAL TECHNIQUE	GOOD METHOD	GOOD METHOD	GOOD METHOD

current techniques, which could reveal the cracks through the uniformly coated neoprene, were proposed by DREP as a rapid method for evaluating the foils in situ, and to complement the more informative radiographic procedures. Figure 12 shows a strip chart recording of the eddy current response to the crack in the foil (Figure 11) through a 0.02-inch neoprene coating. It might be noted that the crack gives a distinctly different signal to that of the weld area.

Discussion

Many corrosion-related problems in the Canadian Forces are currently being evaluated by standard inexpensive non-destructive testing methods.

It might be emphasized that corrosion diagnosis and evaluation is the responsibility of the corrosion specialist and not the NDT technician. Once the corrosion engineer has established the nature of the corrosion problem—and he may utilize NDT to advantage here—it may then be possible to propose NDT to establish the extent of the damage. The economics of the NDT program must, of course, be considered. In order to keep NDT costs within reasonable bounds one must rely on the corrosion engineer, who can often anticipate where the attack will be most severe so that NDT attention can be centred at that location. A large amount of time can be wasted by giving components unnecessary 100% examinations, as might be done by the less knowledgeable NDT specialist who is not working closely with a corrosion engineer.

Table 1 summarizes our experience in using the various NDT methods for the evaluation of corrosion problems.

The examples given in this paper demonstrate that radiography has the distinct advantage among the NDT techniques that it provides overall information, sometimes unexpected information, about corrosion damage and, accordingly, is a very useful first approximation approach in evaluating corrosion problems.

Wastage problems in which metal has wasted relatively evenly over large areas can best be evaluated with ultrasonics. Where the wastage is more selective, as in pitting attack or in corrosion-fatigue cracking, radiography can become more useful. Where attack is very selective, as in intergranular attack, hydrogen embrittlement and stress corrosion cracking, ultrasonic and eddy current testing can be used to greater advantage. Eddy current testing is being used for more and more applications, particularly those where environmental cracking is taking place, and it is believed that we have not fully exploited its worth for corrosion studies.

Each NDT technique has its limitations, and the value of each technique is affected by a number of variables—accessibility, complication of component, size of region of attack; however, most corrosion problems can be reliably evaluated by choosing the most suitable NDT method.

In conclusion, it is believed that, as NDT continues to be used in many quarters of the Canadian Forces for corrosion evaluation, and as more engineers become exposed to the advantages of using the NDT techniques, new applications will be introduced which will help to make our equipment in the Canadian Forces more reliable and our operations more efficient.

Acknowledgements

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